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AFCRL-68-0257

AN INVESTIGATION OF METHODS OF PRODUCING SULFUR TRIOXIDE IN JET EXHAUSTS THROUGH ADDITION OF FUEL ADDITIVES TO JP4

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ABSTRACT

Work was performed to determine the possible
effectiveness of sulfur-containing fuel additives
as contrail suppressents. Such suppression would
require production of significant levels of sulfur
trioxide, a known suppressent, in the exhaust. A
model combustor capable of simulating turbojet oper-
ation at 40,000 feet was designed and built, and a
gas sampling and analysis procedure developed for
measuring the concentration of sulfur trioxide.
Organic fuel additives containing sulfur in various
valence states were tested at many concentration le-
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ytic co-additives such as nitrocompounds and organ-
ometallics. The level of sulfur trioxide in the ex-
haust was found to depend very little on the sulfur
compound used, or its concentration above some thres-
hold value, and the use of co-additives generally
provided no improvement. The use of higher-valent
sulfur compounds seems to have no advantage, and
relatively low concentrations of inexpensive sulfur
compounds, such as 0.5% carbon disulfide, merit oper-
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as a possible basis for improved suppression systems.
Measured yields of sulfur trioxide from the two re-
commended systems are 10 to 20% of the yield from
current chlorosulfonic acid injection techniques,
assuming complete conversion, but may lie much closer
to actual values.

LIST OF CONTRIBUTORS

The work described in this Report was performed by the following personnel at Moleculon Research Corporation:

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I.   INTRODUCTION

The work described in this Report represents
a program devoted to the testing of a variety of
sulfur-containing compounds as potential contrail-
suppressent additives to kerosene-base turbojet
fuels. The known suppressent action of chlorosul-
fonic acid injected into the post-combustion ex-
haust stream appears to confirm the hypothesis that
sulfur trioxide and its hydrates should suppress the
formation of visible contrails; the assumed mechan-
ism of this suppression is discussed below. It
follows that a successful sulfur-containing fuel
additive can be operationally defined as one which
leads to the formation of a level of sulfur trioxide
in the exhaust which is comparable with that believed
obtained by chlorosulfonic acid injection. The gen-
eral program described here has consisted of selec-
tion of additives and co-additives for testing, con-
struction of a combustor capable of burning kerosene-
base fuel under conditions simulating an operational
turbojet, development of a gas-sampling and analytic
technique for determination of exhaust sulfur tri-
oxide levels, and finally the actual testing of ma-
terials in various combinations and at various con-
centrations.

The desirability of a contrail suppression system
for tactical aircraft is apparent. Contrails simplify
the spotting of aircraft under conditions where they

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might otherwise pass unobserved. These contrails
are formed as a result of the condensation of water
vapor ingested by the engine and vastly augmented
by the combustion of a hydrocarbon fuel. Calcula-
tions indicate that autogenous condensation should
not occur in the exhaust stream at the expected
supersaturations. The actual condensation must
therefore occur through heterogeneous nucleation
involving atmospheric dust, salt particles, or en-
gine ash, or alternatively in turbulent regions of
locally high supersaturation. These mechanisms
lead to fewer nuclei than would be the case if auto-
genous nucleation occurred, so that the resultant
droplets are larger and in fact visible. If the
droplets formed were typically smaller than 2500
angstroms, the exhaust would disperse light only
by Rayleigh scattering, and the contrail would be
visible, if at all, as a faint bluish haze.

An effective suppression system must lead to the
formation of droplets below this size limit, which
implies nucleation of at least 10^8 droplets per cubic
centimeter. Present techniques achieve this level
of nucleation by injection of chlorosulfonic acid;
the resultant sulfur trioxide nucleates at a rela-
tively high temperature (if indeed it ever completely
vaporizes in the exhaust), and its highly hygroscopic
character leads to the production of microdroplets
of concentrated sulfuric acid which are effective

nuclei for condensation of water vapor. This system
requires special equipment and the handling of a
corrosive and hazardous liquid; a simpler and more
maintainence-free system is desirable.

One such system would consist of the combustion
of fuel containing soluble sulfur compounds. The
difficulty here is that sulfur trioxide is not the
equilibrium oxidation state of sulfur at temperatures
over about 900^{0}C, so that normal turbojet combustion
would lead initially almost exclusively to sulfur
dioxide. As the combustion gases cool, sulfur tri-
oxide becomes the preferred form, but the rate of
re-equilibration, in the absence of catalysis, is
very slow. It is this combination of factors which
requires the use of catalysts in the commercial pro-
duction of sulfuric acid.

Two possible techniques for obtaining significant
conversion to sulfur trioxide suggested themselves
at the outset of this work. One was the use of or-
ganic sulfur compounds already in the +6 oxidation
state (such as organic sulfates), since an appreci-
able amount of this hexavalent sulfur might well
survive the very brief high-temperature combustion
period; the other was the use of co-additives (such
as nitro-compounds or organometallic compounds)
which could be expected to lead to combustion pro-
ducts capable of catalyzing the conversion of sulfur
dioxide to sulfur trioxide in the cooling exhaust.

Both of these techniques have been studied in the
course of this contract.

II. COMBUSTOR DESIGN

For the actual combustion testing of additives,
the need existed for a laboratory-scale combustor
operable under conditions similar to those existing
within an individual combustion chamber of a turbo-
jet engine. It was decided to attempt simulation
of an engine operating at 40,000 feet, an altitude
at which contrails are encountered, and which re-
quires a smaller air through-put than simulation of
lower altitudes. The components of the combustor as
constructed are shown in the photographs, Figure 1
through 4, and the assembly is shown schematically
in Figure 5.

Figure 1 shows the combustor tail-pipe, the inner
and outer combustion chamber liners, and the slip-
ring bands which control primary and secondary air
flow into the combustion region. One of the thermo-
couple leads, and the ceramic ignition system insul-
ators, can also be seen. The inner liner and the
slip-rings are made of inconel, and the other metallic
components of the system are 316 stainless. Figure 2
shows the assembled system, including the Sutorbilt
rotary positive displacement blower and its motor.
This blower delivers 135 cubic feet of air per minute
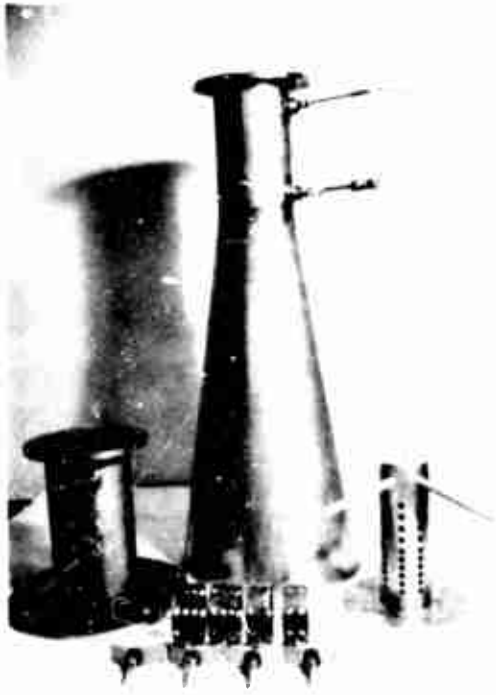at pressures of about 1 psig. Measured pressures be-
tween the blower and the combustion chamber were only
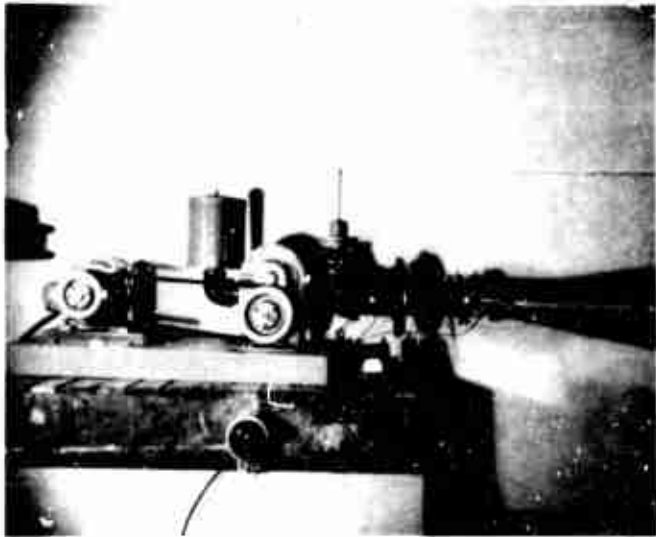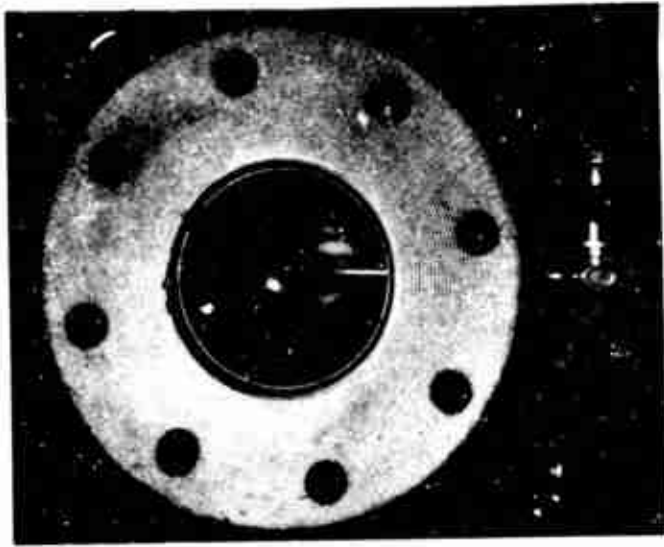
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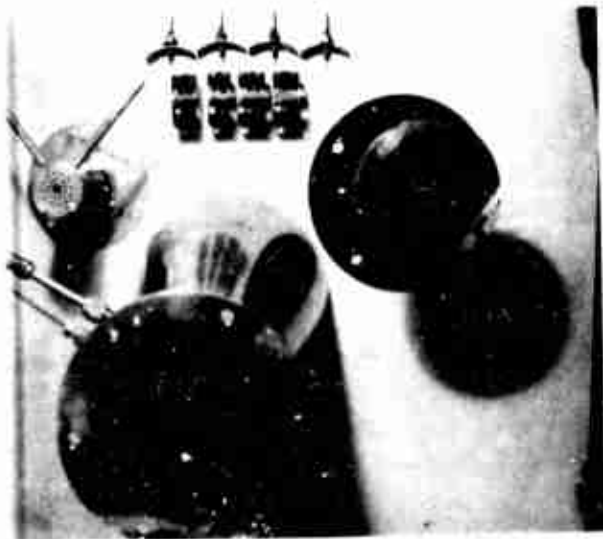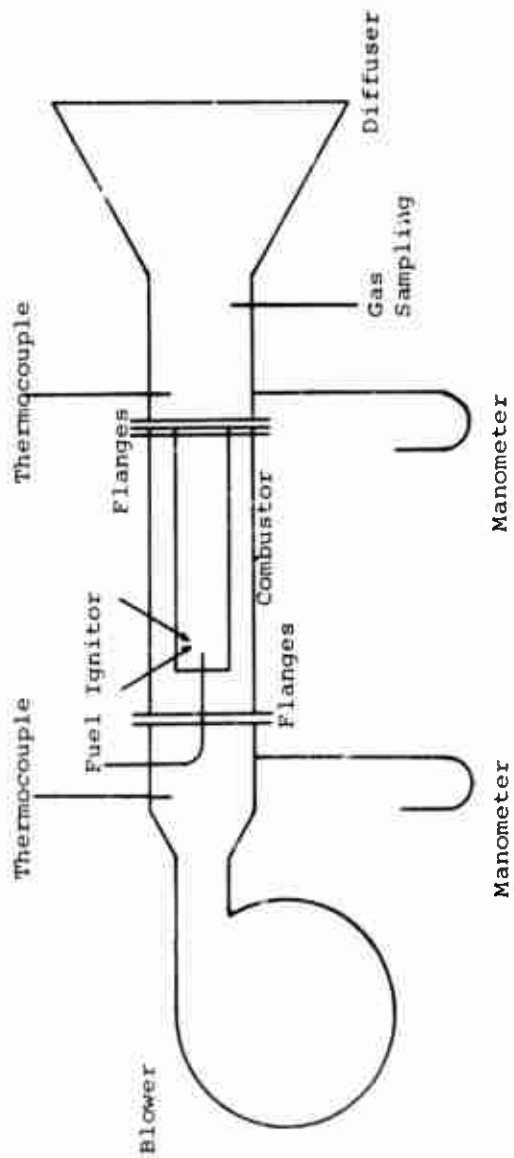Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

SCHEMATIC OF COMBUSTION CHAMBER ASSEMBLY

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slightly above one atmosphere, and little compressive pre-heating of the air occurred; in an actual turbojet this preheating heats the air to about 220°C, but this difference was not expected to materially effect the adequacy of simulation. Figure 3 shows the fuel nozzle, specially constructed by Spray Engineering, as mounted at the forward end of the combustion chamber. This nozzle is smaller than any used in actual engines, and delivered 90 $\pm$ 20 mil per minute at fuel pressures between 50 and 150 psig, obtained with tank nitrogen. This nozzle, and a second nozzle obtained late in the contract, repeatedly clogged, even when protected with a fine-mesh stainless steel filter. This clogging could be cleared with chlorosulfonic acid, but became more frequent with the passage of time.

Figure 4 is another disassembled view of the major components, showing the face plate of the inner liner, and the position of the thermocouple and gas-sampling line within the tail-pipe.

Experimentation showed that optimum conditions prevail with all of the liner holes open for maximum air flow. Under these conditions the laboratory combustor has a combustion temperature of 1500°F to 1800°F and a gas residence time of 2.4 milliseconds, as compared with actual values in an engine at 40,000 feet of 1750°F and 2.0 milliseconds. Thus the model gives a slightly longer dwell time at a slightly

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lower temperature. The small difference in tempera-
ture is accounted for by the lower compressive pre-
heating in the model. Considering the over-all nature
of combustor design technology, the attained simula-
tion is very good.

III. GAS SAMPLING AND ANALYSIS

After consideration of various types of instru-
mental analysis of sulfur trioxide concentration in
the exhaust stream, it was concluded that the most
practical method for work of this scope would consist
of a conventional wet chemical analysis of scrubbing
solutions through which a known fraction of the ex-
haust had been drawn. The two key questions in this
approach were whether a scrubbing system capable of
handling a sufficient volume of exhaust gas, with a
small volume of scrubbing liquid, could do an efficient
job of scavanging sulfur trioxide (a notorious mist-
former), and whether solutions obtained by such a
technique would contain sufficient sulfate for routine
analysis.

It soon became apparent that the requirement for
handling a sufficient quancity of exhaust gas placed
severe constraints on the form of scrubbing system
used. It was calculated that a sampling rate of about
60 liters per minute would be required to obtain an
adequate concentration of sulfate in about one half
liter of scrubbing liquid, and this rate quite ruled
out any elaborate glass-frit gas dispersion system,

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although such systems were initially investigated
while the analysis technique was under development.
The final system consisted of about 150 ml of 4:1
isopropanol:water in each of three 2 liter filter
flasks, each fitted with a half inch glass tube
whose lower opening was beneath the surface of the
liquid and bent nearly parallel with the bottom of
the flask to promote swirling and good agitation
during gas flow.

The neck of each flask was packed with glass
wool to impede transfer of mist between flasks; the
three flasks were connected in series and cooled
during operation to improve the collection of sul-
fur trioxide and reduce evaporation; the first flask
was cooled with dry ice/acetone and the others with
ice. This cooling, by lowering the vapor pressure
of the solvent, significantly reduced the formation
of a sulfuric acid aerosol. The choice of an iso-
propanol:water solvent was based on information in
the literature showing that isopropanol prevents
the oxidative conversion of sulfite to sulfate in
solution, and indeed storage of sulfate/sulfite
solutions up to 48 hours gave no pronounced change
in titer. Analysis of the collected sulfate was
performed on the contents of all three flasks, and
on washings from the glass wool plugs and tubing.
Use of four flasks showed little sulfate in the last
flask, so that three flasks were adopted as stand-

ard except on some early runs in which only two were used.

Two methods were employed for drawing sample gas through this scrubbing system. Initially the outlet from the last flask was connected back into the inlet to the filter on the Sutorbilt blower driving the combustor. This approach, used on early runs, re-cycled about 2% of the exhaust gas through the engine, and interfered somewhat with optimum operation. Sub-sequently a Hurricane Gas Sampler (a small high through-put commercial blower) was substituted, giving improved sampling rates and allowing better engine operation. In both cases the rate of gas sampling was determined by a tantalum-ball rotameter calibrated in our own laboratory, and was typically about 60 liters per min-ute at atmospheric temperature and pressure.

The analytic technique which was used to titrate the sulfate in aliquots from the flasks and washings is described by Fielder and Morgan, Anal. Chim. Acta 23 (1960), pp. 538-540, and the references given in that article. The titration uses barium ions (as bar-ium perchlorate) to titrate sulfate, forming the very stable and insoluble barium sulfate. The end-point is determined using the indicator "Thoron" which changes from its normal yellow color in solution to a pale pink barium complex as soon as excess barium is present. This titration was found to be accurate to a fraction of a milligram of sulfate in about 100 ml of solution, using standard sulfate solutions pre-

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pared by careful dilution, although the end-point
color change is hard to observe at low concentra-
tions. Typical combustor runs yield sulfate solu-
tions ranging from over 30 mg in the first flask
to a few tenths of a milligram in the third flask,
so the sensitivity of the titration is adequate.

The use of standard sulfate solutions demon-
strated the accuracy of the titration, but cali-
bration of the efficiency of the scrubbing train
was more difficult. The gradation between the
amount of sulfate found in the first flask and
that found in the last suggested good scavanging
of sulfur trioxide, and the numbers given in the
next section are reported on the assumption that
recovery of sulfate is almost complete. Careful
transfer of sulfur trioxide into isopropanol:water
solution in the laboratory generally indicated
about 90% recovery, and a 10% correction factor
has been (somewhat arbitrarily) applied to the
reported numbers.

Clearly an improved calibration of the entire
sampling and analysis system was called for and
experiments to provide this information were per-
formed toward the end of the research period. For
this purpose the combustor was modified to allow
injection of dry gaseous sulfur trioxide into the
exhaust stream behind the combustion chamber. This
sulfur trioxide was obtained by passing dry nitro-
gen through warm "fuming sulfuric acid" (a solution

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of sulfur trioxide in sulfuric acid). This flow
of nitrogen containing sulfur trioxide was main-
tained during operation of the combustor for a
period of time similar to a typical additive run,
both with and without an actual flame, and the to-
tal sulfur trioxide introduced was determined by
the loss in weight of the sample of fuming sulfuric
acid, quantitative transfer having been demonstrated
previously by absorption on Ascarite. Quantities
were used which bracket the amounts found in prac-
tice.

During these calibration runs the tail-pipe of
the combustor was extended with a two foot length
of 4" i.d. Transite pipe lined with stainless steel,
and sample gas was withdrawn from the further end
of this extension. The purpose of this extension
was to allow adequate opportunity for mixing of the
sulfur trioxide vapor with the exhaust stream, in
order to ensure an authentic sample. This extension
was left in the combustor during later additive runs.

The results of these experiments are shown in
Figure 6, which is a plot of percent sulfur trioxide
recovered _versus_ the quantity introduced, with the
latter being given in terms of the number of milli-
grams of sulfate expected to pass into the sampling
system. The error bars represent as assumed $\pm 10\%$
system error coupled with a $\pm.1$ gm weighing error in
the fuming sulfuric acid. It can be seen that a
broad maximum recovery is found near 35 mg, and that
this maximum indicates about 55% recovery. This is

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FIGURE 6   CALIBRATION CURVE BASED ON SULFUR TRI-
           OXIDE INTRODUCTION
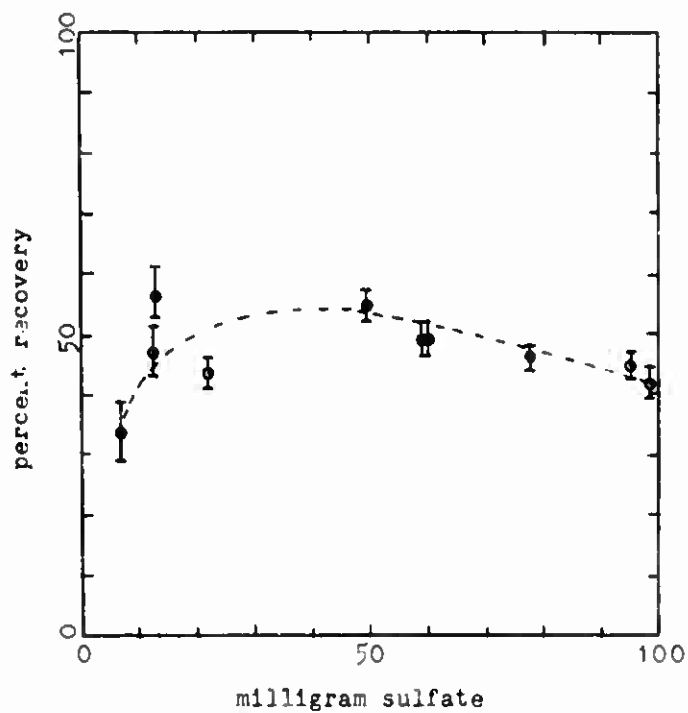
in the range of SO_3 recovery corresponding to oper-
ation of the combustor with fuel additives. In all
of these calibration runs substantially more sul-
fate was found in the glass wool from the flasks
than occured during standard operation. This sug-
gests that recovery was poorer during the calibra-
tions than during combustion with fuel additives,
perhaps because of a greater tendency for mist for-
mation before the sulfur trioxide introduced for
calibration had time to disperse to a uniform low
concentration. In any case this remains an open
question, and all that can be said is that recovery
is almost certainly in the range between 50% and
100%. The factor-of-two correction indicated by
Figure 6 has not been applied to the numbers re-
ported in the next Section.

IV. SUMMARY OF RESULTS

Tests were conducted on a total of seven sulfur-
containing additives (one of which was gaseous sul-
fur dioxide) and six co-additives with potential
catalytic properties, at a total of thirty-one dif-
ferent combinations and concentrations. Ninety-two
additive runs were made and analyzed, plus ten cali-
bration runs involving injection of sulfur trioxide.
Most runs were performed at least in duplicate or
triplicate.

This body of data is presented in Table 1, and
a word should be said here about the form of the

TABLE 1

	Additive	Co-additive	Gm(S)/L	Gm(S-VI)/L	Comments
1)	2.5% Thiophene	None	10.0	0.48	
2)				0.60	
3)				0.48	
4)				0.54	
5)	5.0% Thiophene	None	20.1	0.77	Early Run
6)				0.99	Early Run
7)				1.18	Early Run
8)				1.09	
9)				1.04	
10)				0.81	Silica Wool Trap
11)				0.56	
12)				0.61	
13)	7.5% Thiophene	None	30.1	0.58	
14)				0.57	
15)				0.71	
16)				0.65	
17)	10.0% Thiophene	None	40.2	0.97	
18)				0.62	
19)				1.14	
20)				0.86	Silica Wool Trap
21)				0.94	Pyrex Wool Trap
22)				0.49	
23)				0.59	
24)				0.53	
25)				0.61	

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TABLE 1 (Continued)

	Additive	Co-additive	Gm(S)/L	Gm(S-VI)/L	Comments
26)	5.0% Tetrahydro-thiophene	None	18.2	0.63	
27)				0.62	
28)	10.0% Tetrahydro-thiophene	None	36.4	0.67	
29)				0.55	
30)	0.5% Carbon Disulfide	None	0.53	0.29	
31)				0.30	
32)	2.6% Carbon Disulfide	None	0.06	0.40	
33)				0.40	
34)	0.5% Carbon Disulfide	None	5.3	0.55	
35)				0.63	
36)	2.0% Carbon Disulfide	None	21.2	0.68	
37)				0.77	
38)	4.0% Carbon Disulfide	None	42.4	0.63	
39)				0.74	
40)				0.57	Double Run
41)				0.59	Double Run
42)	8.0% Carbon Disulfide	None	84.9	0.84	
43)				0.40	Steel Wool Trap
44)				0.47	Steel Wool Trap
45)				0.96	
46)				0.58	
47)				0.45	Stainless Steel Insert

TABLE 1 (Continued)

	Additive	Co-additive	Gm(S)/L	Gm(S-VI)/L	Comments
48)	8.0% Carbon Disul-fide	None	84.9	0.62	Stainless Steel Insert
49)				0.43	Stainless Steel Insert
50)				0.60	Stainless Steel Insert
51)				0.44	Holder in Flame
52)				0.55	Holder in Flame
53)				0.61	Stainless Steel Insert
54)				0.63	Inconel in Flame
55)				0.74	Holder in Flame
56)	16.0% Carbon Disul-fide	None	169.8	0.70	
57)				0.59	
58)	5.0% Amyl Sulfate	None	ca. 7.0	0.19	Early Run
59)				0.14	Early Run
60)				0.09	
61)				0.23	
62)				0.10	
63)				0.14	
64)				0.19	
65)	5.1% Isoamyl Sulfone	None	ca. 8.0	0.54	
66)				0.59	
67)	5.0% Butyl Sulfite	None	ca. 8.5	0.58	
68)				0.53	
69)	2.5% Thiophene	5.0% Nitropropane	10.0	0.45	

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TABLE 1 (Continued)

	Additive	Co-additive	Gm(S)/L	Gm(S-VI)/L	Comments
70)	5.0% Thiophene	5.0% Nitropropane	20.1	2.26	Early Run
71)				0.91	Early Run
72)				0.38	
73)				0.45	
74)	5.0% Thiophene	5 ml Tetrabutyltin	20.1	0.81	
75)				0.55	
76)	5.0% Thiophene	10 ml Tetrabutyltin	20.1	0.56	
77)				0.43	
78)	5.0% Thiophene	5 gm Tetrabutyllead	20.1	0.38	
79)				0.36	Steel Wool Trap
80)	5.0% Amyl Sul-fate	5.0% Nitropropane	ca. 7.0	0.31	Early Run
81)				0.23	
82)	5.0% Tetrahydro-thiophene	5.0% Nitropropane	18.2	0.45	
83)	4.0% Carbon Di-sulfide	.25 gm Platinum(Ac)$_2$*	42.4	1.09	
84)				0.53	Late Run
85)	4.0% Carbon Di-sulfide	0.1 gm Vanadyl(Ac)$_3$*	42.4	0.47	
86)	4.0% Carbon Di-sulfide	" Saturated	42.4	0.43	

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TABLE 1 (Continued)

	Additive	Co-additive	Gm(S)/L	Gm(S-VI)/L	Comments
87)	4.0% Carbon Di-sulfide	0.1 gm Ferric(Ac)$_3$*	42.4	0.39	
88)				0.43	
89)	18.5 gm Sulfur Dioxide	None	9.25	0.42	Before Flame
90)	70.3 gm Sulfur Dioxide	None	35.1	1.88	Before Flame
91)	23.7 gm Sulfur Dioxide	None	11.8	0.59	After Flame
92)	54.5 gm Sulfur Dioxide	None	27.2	0.81	After Flame

* Ac = Acetylacetonate

presentation. Most runs were made with one liter
of fuel, generally made up as a certain volume
percent additive and co-additive when these were
liquids, and by weight in the case of solids. This
composition is indicated in the first and second
columns. The third column gives the number of
grams of sulfur actually present per liter of fuel,
based on the percent sulfur in the additive and its
specific gravity. The fourth column gives the num-
ber of sulfur per liter of fuel which was found to
have emerged from the combustor as sulfur trioxide.
This is a significant figure-of-merit; a number
near 5.0 would represent a concentration of sulfur
trioxide in the exhaust comparable to that theore-
tically obtained from present chlorosulfonic acid
injection systems. The ratio of the numbers in
column four to those in column three gives the
percent conversion of sulfur to its trioxide in
each case. The last column is reserved for com-
ments on the individual runs. The comment "Early
Run" indicates one of the first few runs in which
less than three collection flasks were used, and
operation was less well controlled. The comment
"Late Run" refers to one of the last few runs, after
evidence indicated that the combustor had been poi-
soned in some way and yields were reduced; this is
discussed in the next Section. Comments referring
to "Trap" (e.g., steel wool trap) point out those
runs in which a filter was interposed between the

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combustor and the first collection flask to stop
possible fly-ash, and give the material used in
the filter. Within each category in the Table, the
listing is in chronological order. The comment
"Double Run" refers to a run in which two liters of
fuel plus additive were burned over twice the usual
period of time. Other comments are explained in
the next Section.

V. DISCUSSION AND CONCLUSIONS

    The data presented in Table 1 lead at once to
certain observations. Setting aside the early runs
with less than three scrubbing flasks and incom-
pletely developed procedures, there remains consid-
erable scatter in the numbers obtained; within this
scatter, the most notable tendency is the constancy
of the "grams of hexavalent sulfur per liter" num-
bers, which quite generally lie in the range 0.55
$\pm$ 0.15. This constancy, which covers additives of
very different structure and extends over a concen-
tration range of two orders of magnitude, strongly
suggests that the mechanism leading to observed
sulfur trioxide is zeroth order in its rate con-
trolling step; indeed, formation of products at a
rate which is independent of reactant concentration
is the definition of a zeroth order reaction. Such
zeroth order reactions are commonly associated with
processes which occur only on walls or catalytic
surfaces under conditions in which the available

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surfaces are saturated. Since the most likely can-
didate for surface catalysis in the laboratory com-
bustor was the metal surfaces near the combustion
zone, runs 47 through 55 were made with various
metal surfaces mounted directly in the combustion
chamber exit. The runs marked "Stainless Steel
Insert" were made with steel wool of high surface
area, those marked "Holder in Flame" were made with
a perforated stainless steel plate, and the inconel
run was made with a sample of inconel turnings of
moderately large surface. These runs did not show
any marked change in sulfur trioxide yield.

The two concepts initially proposed as most pro-
mising, namely the use of hexavalent sulfur compounds
and/or catalytic co-additives, likewise did not prove
out. Amyl sulfate, with its absolute yield of about
0.2 grams of hexavalent sulfur per liter of fuel
(about a 3% conversion of the sulfur in the additive
to sulfur trioxide), was among the poorest additives
studied. The sulfone and sulfite studied in runs
65 through 68 were much better than the sulfate, but
no better than typical lower-valent sulfur compounds
such as thiophene and carbon disulfide. The use of
catalytic co-additives is covered in runs 69 through
88; compounds tested included nitropropane, a possible
source of catalytic nitrogen oxides, and organometallic
derivatives of ^roup IV metals, transition metals, and
platinum. Only one of these runs gave a notably high
absolute yield; this was the first test of 0.25 gm

of platinum diacetylacetonate in a liter of 4% car-
bon disulfide, and gave 1.09 grams of hexavalent
sulfur per liter of fuel, not a high conversion,
but an encouraging total amount. This system was
not restudied until completion of the iron and van-
adium tests, at which time studies with carbon di-
sulfide with no co-additive showed that sulfur tri-
oxide yields were down by about 40%. It must be
assumed that one of the additives poisoned whatever
surface was involved in sulfur trioxide formation,
and time did not remain for remedial action. Thus
the initial high value for the platinum compound
may be correct; nevertheless economics preclude any
practical application of such a system.

Runs 30 through 35 were made in an effort to de-
termine just how low one could drop the total con-
centration of sulfur in the fuel without reducing
the total output of sulfur trioxide. It had already
been determined on several occasions that combustion
of pure kerosene produced no sulfate titer in the
scrubbing liquid. It can be seen from this data
that when total sulfur in the fuel, present as car-
bon disulfide, is reduced to about 0.5 gm per liter,
the yield of sulfur trioxide drops by about a factor
of two from its limiting value at higher concentra-
tions. At this level the percent conversion becomes
quite large, exceeding 50%. It can also be seen that
the use of 0.5 volume % carbon disulfide in kerosene
gives about as much sulfur trioxide as the higher

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concentrations. This would be an inexpensive and convenient fuel additive and should be considered for flight tests. It remains to be determined whether the amount of sulfur trioxide produced will be adequate for suppression.

To achieve the theoretical yield of sulfur trioxide from current chlorosulfonic acid injection systems, a value near 5.0 grams of hexavalent sulfur per liter of fuel is required. The carbon disulfide system mentioned above produces only about 11% of this amount. On the other hand the injection of chlorosulfonic acid is no doubt accompanied by some decomposition to sulfur dioxide, and it is possible that not all of the liquid acid is vaporized or dispersed sufficiently to participate in suppression. Moreover, the amount of chlorosulfonic acid used presently includes some margin, particularly since the amount of suppressent needed varies with altitide and humidity. Combining all of these factors with the uncertainty as to how much better (or worse) a carbon disulfide system might perform in actual operational turbojet engines, flight testing of 0.5% carbon disulfide is indicated.

The last data from Table 1 to deserve consideration are the final four runs with gaseous sulfur dioxide injection. These were made after the possible poisoning of the combustor, and may therefore be somewhat low. In any case the yield of 1.88 grams of sulfur in the form of the trioxide, obtained by

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injecting 70 grams of dry sulfur dioxide into the
intake airstream during the combustion of a liter
of kerosene, is the highest absolute concentration
of sulfur trioxide found for any system tested.
This suggests that the sulfur compounds tested
may function almost entirely by complete conver-
sion to sulfur dioxide, followed by some process
which converts a small portion of the dioxide into
the trioxide. If this process occurs in certain
regions of the combustion chamber, for example
near the ports where secondary air enters, it is
easy to see why sulfur dioxide entering with the
secondary air might be more effective as a source
of sulfur trioxide. This is only speculative; more
research would be required to support or reject the
notion, but in practical terms the use of a system
for injecting sulfur dioxide into turbojet intakes
would be much simpler than the injection of chloro-
sulfonic acid into the exhaust. Sulfur dioxide is
inexpensive and easy to handle, and there would
be a minimum of opportunity for interference with
engine operation by corrosion or gumming. It there-
fore seems prudent to recommend this sulfur dioxide
system, along with the carbon disulfide system al-
ready mentioned, for further study either in the
laboratory or in flight tests.

In summary, it has been found that the use of
higher-valent sulfur compounds as fuel additives
seems to have no advantage over the use of lower-

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valent compounds for the purpose of producing sulfur trioxide in the exhaust, and that the use of nitrogenous or organometallic co-additives does not generally improve yields of the trioxide. On the other hand, relatively low concentrations of inexpensive sulfur compounds such as 0.5% carbon disulfide offer as much promise as other systems, and merit operational testing. On the basis of limited data, the injection of sulfur dioxide into intake air appears significantly more effective than combustion of sulfur-containing fuels, and should be investigated as a possible basis for a contrail suppression system superior to the post-combustion injection of chlorosulfonic acid.

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13. ABSTRACT

The possible effectiveness of sulfur-containing fuel additives as contrail suppressents was investigated by analysis of sulfur trioxide concentration in the exhaust from a model combustor. This specially constructed combustor simulated turbojet operation at 40,000 feet. Exhaust was analyzed by scrubbing a known fraction through cold isopropanol/water and titrating total sulfate with barium perchlorate. Sulfur trioxide production was found to depend very little on the concentration or composition of the additive. The best systems, recommended for further study, were 0.5% carbon disulfide, and injection of sulfur dioxide into intake air. These give sulfur trioxide levels which are 10 to 20% of those obtained with currently operational systems based on injection of chlorosulfonic acid into the exhaust, assuming that all of the sulfur in the chlorosulforic acid becomes available as the trioxide. (Author)

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14	LINK A		LINK B		LINK C	
KEY WORDS	ROLE	WT	ROLE	WT	ROLE	WT
Contrails						
Contrail Suppression						
Fuel Additives						
Sulfur Compounds						
Combustion						
Gas Analysis						
Sulfate Analysis						
Sulfur Trioxide						